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Special Report #32

LARGE-SCALE BOUNDARY-LAYER CONTROL TESTS ON TWO
WINGS IN THE N.A.C.A. 20-FOOT WIND TUNNEL

By Hugh B. Freeman
Langley Memorial Aeronautical Laboratory

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LARGE-SCALE BOUNDARY-LAYER CONTROL TESTS ON TWO WINGS IN THE N. A. C. A. 20-FOOT WIND TUNNEL

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SUMMARY

Tests were made in the N.A.C.A. 20-foot wind tunnel on: (1) a wing, of 6.5-foot span, 5.5-foot chord, and 30 percent maximum thickness, fitted with large end plates and (2) a 16-foot span 2.67-foot chord wing of 15 percent maximum thickness to determine the increase in lift obtainable by removing the boundary layer and the power required for the blower.

The results of the tests on the stub wing appeared more favorable than previous small-scale tests and indicated that: (1) the suction method was considerably superior to the pressure method, (2) single slots were more effective than multiple slots (where the same pressure was applied to all slots), the slot efficiency increased rapidly for increasing slot widths up to 2 percent of the wing chord and remained practically constant for all larger widths tested, (3) suction pressure and power requirements were quite low (a computation for a light airplane showed that a lift coefficient of 3.0 could be obtained with a suction as low as 2.3 times the dynamic pressure and a power expenditure less than 3 percent of the rated engine power), and (4) the volume of air required to be drawn off was quite high (approximately 0.5 cubic feet per second per unit wing area for an airplane landing at 40 miles per hour with a lift coefficient of 3.0), indicating that considerable duct area must be provided in order to prevent flow losses inside the wing and insure uniform distribution of suction along the span.

The results from the tests of the large-span wing were less favorable than those on the stub wing. The reasons for this were, probably: (1) the uneven distribution of suction along the span, (2) the flow losses inside the wing, (3) the small radius of curvature of the leading edge of the wing section, and (4) the low Reynolds Number

of these tests, which was about one half that of the stub wing. The results showed a large increase in the maximum lift coefficient with an increase in Reynolds Number in the range of the tests.

The results of drag tests showed that the profile drag of the wing was reduced and the L/D ratio was increased throughout the range of lift coefficients corresponding to take-off and climb but that the minimum drag was increased. The slot arrangement that is best for low drag is not the same, however, as that for maximum lift.

INTRODUCTION

Boundary-layer control tests made with small models at this laboratory (T.N. 323) and abroad (T.M. 634) have shown that this method offers a powerful means of increasing the maximum lift and the range of angles of attack for safe flying.

The present report presents some of the results of an investigation conducted in the N.A.C.A. 20-foot wind tunnel on two large model wings made to determine the practicability of the method, the lift increase that may be realized, and the power required to control the boundary layer.

The preliminary tests were made on a wing, of 6.5-foot span, 5.5-foot chord and a maximum thickness of 30 percent chord, fitted with large end plates to increase its effective aspect ratio. The great thickness and short span facilitated the tests by allowing: (1) the blower to be installed directly inside the wing and (2) a great number of variables to be studied in the shortest possible time.

The second wing section was chosen to be representative of the conventional wings found in practice although it was realized that this feature did not meet the optimum requirements for boundary-layer control. The two wings then represent the two extremes of thickness and camber. The optimum wing for boundary-layer control will probably be somewhere between the two.

MODELS

6.5-Foot Wing

The model used for the preliminary tests (figs. 1 and 2) had a maximum thickness of 30-percent chord, a 6.5-foot span, a 5.5-foot chord and was fitted with end plates to increase the effective aspect ratio. The motor-driven fan was mounted inside the wing and could be made to induct or discharge air at the end of the wing according to whether the boundary layer was being energized by ejecting the air through spanwise backward-opening slots or removed by sucking it into the wing through spanwise normal-opening rectangular slots.

16-Foot Wing

The model for the second series of tests consisted of a 16-foot span, 2.67-foot chord wing with the N.A.C.A. 2415 airfoil section (i.e., 2 percent maximum camber at the 40 percent chord station and 15 percent maximum thickness) having a streamline fuselage attached to the bottom of the wing in which the blower was mounted. The fan in this case discharged the air in a backward direction at the tail of the fuselage (fig. 3). The wing was fitted with a 30 percent hinged trailing-edge flap that could be deflected 15° , 30° , 45° , or 60° . A removable 25 percent chord split flap was also provided.

TESTS

With the stub wing, tests were made both by the method of energizing the boundary layer by discharging jets of air in a backward direction along the top surface of the wing and by sucking the boundary layer into the wing. Various slot locations, slot sizes, and wing pressures were tried in both cases.

Measurements were made of the lift of the wing, the power input to the blower, the wing pressure, and the volume of air handled by the blower. The tests were made at an air speed of approximately 40 miles per hour.

In the second series of tests only the suction method

was used. Various slot locations, wing pressures, and flap deflections were tested. The split flap was only tested at one angle (50° to chord line).

The greater part of these tests was made at a wind speed of 30 miles per hour. This low speed was desirable in order to make the ratio of wing pressure to the dynamic pressure as large as possible. A few tests were made at several higher speeds in order to determine the effect of scale on the maximum lift.

A few tests were made at an air speed of approximately 80 miles per hour to determine the effect of boundary-layer control on the drag characteristics, especially in the range of lift coefficients corresponding to the take-off and climbing conditions.

RESULTS AND DISCUSSION

6.5-Foot Wing

The results of lift and drag measurements are presented in the form of the usual nondimensional coefficient. The wing pressure is given in terms of the dynamic pressure, i.e.,

$$\frac{P}{q} = \frac{\text{wing pressure above static pressure (?)}}{\text{dynamic pressure of air stream}}$$

and may be either positive or negative according to whether the boundary layer is being blown or sucked off. Two additional coefficients are also used: (1) a power or equivalent drag coefficient formed from the blower power, the tunnel velocity and the wing area,

$$^{(1)} C_{DS} = \frac{\text{input power to blower (ft.-lb./sec.)}}{qSV}$$

(2) a volumetric coefficient

$$C_Q = \frac{\text{volume of air (cu.ft./sec.)}}{SV}$$

The coefficient (C_{DS}) as previously defined is ob-

⁽¹⁾ Based on power input to blower and therefore is a function of an overall efficiency factor covering blower, intake & delivery.

(² Based on input to the wing. Since p is measured relative to free stream and wing is actually moving with q has to be measured with respect to free air and therefore will have $p+q$.⁵
This is independent of the overall efficiency factor.

visiously affected by the efficiency of the blower; hence should not be used in comparing results obtained with different arrangements of the blower. For such comparisons the blower efficiency should be eliminated by computing the coefficients for an "ideal" blower. This coefficient is simply the product

$$C_{D_S} (\text{ideal}) = C_Q \left(\frac{P}{q} + 1 \right)^{-1} \quad ^2)$$

This coefficient is only used in this section in comparing the present results among themselves and with previous model results. Unless otherwise indicated, C_{D_S} is based on the input power to the blower.

Pressure slots.— Typical lift curves for the backward opening slots are shown in figure 4 for four values of the wing pressure (P/q) and are compared to the lift without control. The effective aspect ratio of the stub wing with end plates is approximately 3.5. This value explains the low lift-curve slope. For an aspect ratio of 6.0 the lift coefficient $C_L = 3.0$ would occur in the neighborhood of 32° angle of attack.

The maximum lift obtainable with a given power coefficient is shown in figure 5 for various slot sizes at the 42-percent chord location. Within the range tested the $\frac{1}{2}$ -inch slot (i.e., 0.75-percent chord) appears to be the best width.

Large section slots.— A typical set of lift curves for the suction type slot is shown in figure 6 and the maximum lift is plotted against power coefficient in figure 7. The most interesting features of these curves are the low suction pressures and low power coefficients required in comparison with those of the pressure slots. Figure 8 presents a comparison of the results of the suction and pressure methods of control with previous test results. The coefficients of power are all computed for an ideal blower. The suction slots are seen to be several times more efficient than the pressure slots. The reason for this difference is that both the pressure difference and the volume of air required are greater by the pressure method than by the suction method. A comparison of the volumetric coefficients is given in figure 9.

Slot location.— The best slot location for maximum lift is indicated by figure 10 to be at about the 54-percent chord station.

Slot size.— The efficiency of the slot increases rapidly with slot size up to about 2 percent of the chord; then remains approximately constant for all the larger sizes tested (fig. 11).

Multiple-slot arrangements.— A few multiple-slot arrangements were tried with both methods of control. The results for the best of these are shown in figure 12. None of these arrangements appears as favorable as the best single-suction slot.

It is obvious that these results do not represent the optimum that may be obtained from multiple slots since it was not practicable in these tests to apply to each individual slot the correct suction according to its location on the wing chord. Further tests along this line were considered outside the scope of the present investigation.

The results for a perforated cover (i.e., a series of 1/32-inch spanwise slots spaced 2 inches apart along the wing chord) are included in fig. 8.

A few tests were made with a forward-opening suction slot at the 50-percent chord location. A 1-inch slot gave results (not shown) better than the best pressure-type slot but not as good as the best normal-opening suction slot.

Summary of preliminary tests.— In spite of the unusual wing section and short span of the wing model, several interesting facts were brought out by the preliminary tests: (1) The suction-type slot appeared to be several times more effective than the backward-opening pressure-type slot. (2) A single large suction slot appeared to be better than any multiple-slot arrangement when the same suction was applied to all slots. (3) The efficiency of a slot increased very rapidly for increasing widths up to 2 percent of the wing chord and remained approximately constant for all larger sizes tested. (4) For this thick section with its well-rounded leading edge, the best slot location was near the midchord of the wing.

Tests on a 16-Foot Wing

In accordance with the finding of the preliminary tests only the suction type of slot was investigated with the 16-foot wing.

It was anticipated that in going to a large span and a comparatively thin wing, some difficulty would be experienced in obtaining uniform distribution of the quantity of air sucked off the wing along the span because of the flow losses inside the wing and the increase in the velocity of flow from the tip to the center of the wing. In order to minimize this effect the slots were tapered from a width of 0.0234C at the center to 0.035C near the tip. The shape of slot was determined by adjusting the taper until the product of the square root of the wing pressure and the slot width at all points along the span was constant. This result was determined with the wind tunnel running and the wing set at a high angle of attack below the burble point. It should be noted that the thin rectangular wing is thus handicapped at the start since an excess suction must be provided throughout the span in order to provide the minimum suction required near the wing tips. The tapered slot minimizes this effect to some extent but does not eliminate it.

The results of the tests on the 16-foot wing are presented in figures 13 to 24. For convenience the results are divided into four parts. The first part deals with the normal wing (figs. 13 and 14), the second with the plain flap (i.e., hinged trailing edge) (figs. 15, 16, and 17), the third with a 25 percent split flap (figs. 18 to 22), and the fourth with the effect of boundary-layer control on the drag and L/D for the conditions of gliding flight, take-off, and climb (figs. 23 and 24).

Plain wing.— The effect of removing the boundary layer from the 16-foot wing is principally a small increase in the slope of the lift curve and the delay of the stall. There is also a slight shift of the angle of zero lift to lower values but this effect is slight compared with what it was on the thick wing. The lift curves are shown in figure 13 for six slot locations. The blower speed is constant for all of the tests and the power approximately so. The maximum lift increases as the slot is moved forward on the chord. The best slot location appears to lie between the 20-percent and the 11-percent chord locations. This result is also indicated by the curves of

maximum lift against power (fig. 14). All the power coefficients in this section are computed from the air pressure and volume.

The low maximum lift obtained without control is probably due to the low Reynolds Number of the tests (about 650,000). A rapid increase in the maximum lift with increasing Reynolds Number is shown by the curve in figure 15. This increase indicates that these lift results should be increased from 15 to 20 percent when comparing them with those of the thick wing in the previous section.

Plain flap.— The lift curves for various flap deflections, with and without control, are shown in figure 16. The slot for this condition is located on the flap itself, 3 percent aft of the hinge axis or 73 percent aft of the leading edge of the wing. These curves and those in figure 17, for which the slot was located on the main wing at 20 percent of the chord, afford an interesting comparison. For the latter condition the maximum lift for all the flap deflections is somewhat greater than for the wing without the flap and, in all cases, the stall occurs above 30° angle of attack. The slope of the lift curves, however, is less than that of the 0° flap setting, probably because of the separation of the flow on the flap itself. Contrast the slope of these curves and their separation with that of the lift curves in figure 16. Here the slope of the curves is the same as for the 0° flap angle and the curves are separated by a distance about three times as great as in the former case. Only two of the flap angles, 30° and 45° , give maximum lifts greater than that of the best condition for the wing alone, but these maximum lifts are obtained at very much lower angles of attack.

Slot locations near the trailing edge appear to be more effective in maintaining a high lift-curve slope; whereas those near the leading edge are more effective in holding the flow at high angles of attack. From this result it would appear desirable, on this section at least, to use two slots, one at the front and one at the rear.

From considerations of blower power required to obtain a maximum lift, the flap arrangements all appear to be better than the wing alone (fig. 18).

Split flap.— It is interesting to note that the slope of the lift curves, using a split flap, is very little

different with and without control and that practically the whole increase in lift with control is obtained by delaying the burble to higher angles of attack (fig. 19). This arrangement was the most favorable tested both with respect to maximum lift and blower power (figs. 20 and 21). As in the case of the plain wing, the best slot location is near the 20-percent chord line. This result is shown in a different manner in figure 22 where the maximum lift for a constant blower power ($C_{D_S} = 0.15$) is plotted against slot location.

Comparing the best of these results (fig. 21) with the best of those obtained with the thick wing (fig. 8), it is clear that even though the present lift coefficients were increased 20 percent to allow for the difference in the scale of the tests, the power required to obtain a given lift coefficient would still be several times that required with the thick wing. This result is not surprising considering the small radius of curvature of the leading edge of the present wing in comparison with that of the thick one and the difficulty, mentioned before, of obtaining uniform suction along the span.

Effect on angle of glide.— The gliding-flight characteristics of the wing with the fuselage are shown in figure 23 with and without control for the normal wing and the wing with split flap. The L/D , hence the gliding angle at the maximum lift of the normal wing, is almost identical with and without control. In case of the split flap, however, there is a small decrease in L/D at the maximum lift with control; hence the gliding angle would be increased slightly with control. It should be noted that the drag coefficients plotted here are computed from the measured drag and do not include the equivalent drag to account for the power of the blower, hence are not applicable to power flight. The negative drag coefficients that occur at low angles of attack simply indicate that the reaction of the blower jet, for this high blower power coefficient, is greater than the drag of the wing, i.e., the jet is propelling the wing. This condition is of little practical significance since it is hardly conceivable that such a propulsive system could be made as efficient as a simple screw propeller; with the present-day airplane at least.

Effect on drag and L/D ratio.— All of the foregoing discussion has had mainly to do with the landing, or power-

off flight, condition, where considerations of drag are of only minor importance. In a consideration of the power-on flight conditions of take-off and climb, however, the drag characteristics are of major importance. To the drag of the wing, therefore, must be added an equivalent drag coefficient to account for the power expended by the blower. This drag coefficient is identical with the power coefficient

$$C_{DS} = \frac{P}{qSV}$$

that has been used in the previous paragraphs. That it may also be used as a drag coefficient is seen from the following identity

$$C_{DS} = \frac{P}{qSV} = \frac{D_e V}{qSV}$$

where D_e is defined as an equivalent drag.

Furthermore, since the blower power varies as the cube of the speed of translation, the high coefficients necessary for the maximum lift condition are of little interest in the range of take-off and climb. Hence a special series of tests were run for this condition. These tests were made at a tunnel speed of about 80 miles per hour and the slot was located near the trailing edge of the wing (91-percent chord). This slot location was chosen for several reasons. First, the previous tests indicated that for the same blower power the lift-curve slope increased slightly as the slot was moved away from the leading edge. Second, with respect to economy of blower power the trailing-edge location appears to be the most logical place to take in the air, since the velocity in the boundary layer is lowest at this point and the pressure on top of the wing is highest. The exhaust velocity of the blower was approximately equal to the tunnel velocity for these tests.

The polars with and without control are compared in figure 24. The abscissa in this case is the sum of the measured drag coefficient plus the equivalent drag coefficient ($C_D + C_{DS}$). The profile drag is considerably reduced throughout the range of lift coefficients corresponding to take-off and climb and, in consequence, the L/D ratio is correspondingly increased. The minimum drag is increased somewhat by boundary-layer control.

CONCLUSION

It is interesting to compute how much power would be required to control the flow on an actual airplane. The following example is worked out for a light airplane. Assume

Wing area	160 sq. ft.
Wing loading, W/S,	10 lb./sq. ft.
Maximum C_L	3.0
Blower efficiency	65 percent
Engine horsepower	95

From curve A in figure 8 the blower power coefficient required for a lift coefficient of 3.0 is

$$C_{DS} = 0.028 = \frac{\text{power}}{qSV} = \frac{\text{power}}{S \frac{1}{2} \rho V^3}$$

V in this case is the stalling speed which for the foregoing wing loading and lift coefficient is 53.1 ft./sec.

$$\begin{aligned} \text{Blower power then} &= \frac{C_{DS} S \frac{1}{2} \rho V^3}{\text{blower efficiency}} \\ &= 1,230 \text{ ft. lb./sec.} \\ &= 2.24 \text{ horsepower} \end{aligned}$$

The volumetric coefficient for the same lift is obtained from figure 9.

$$C_Q = \frac{Q}{VS} = 0.0085$$

$$\text{the volume} = Q = 0.0085 \times 53.1 \times 160 = 72.2 \text{ cu. ft./sec.}$$

The suction required is

$$(-P/q) = \frac{C_{DS}}{C_Q} - 1 = \frac{0.028}{0.0085} - 1 = 2.3$$

or $(-P) = 2.3 \times 3.36 = 7.72 \text{ lb./sq. ft.}$

From this example it is seen that the power and suction required are extremely low. The volume of air handled per unit of time, however, is quite high and indicates the need of considerable duct area in order to keep the flow losses inside the wing at a minimum and keep a uniform suction throughout the span. This requirement can possibly be met by using a tapered wing. Such a wing is now under construction. This wing also has a higher camber and thickness than most conventional wings.

Langley Memorial Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., March 20, 1935.

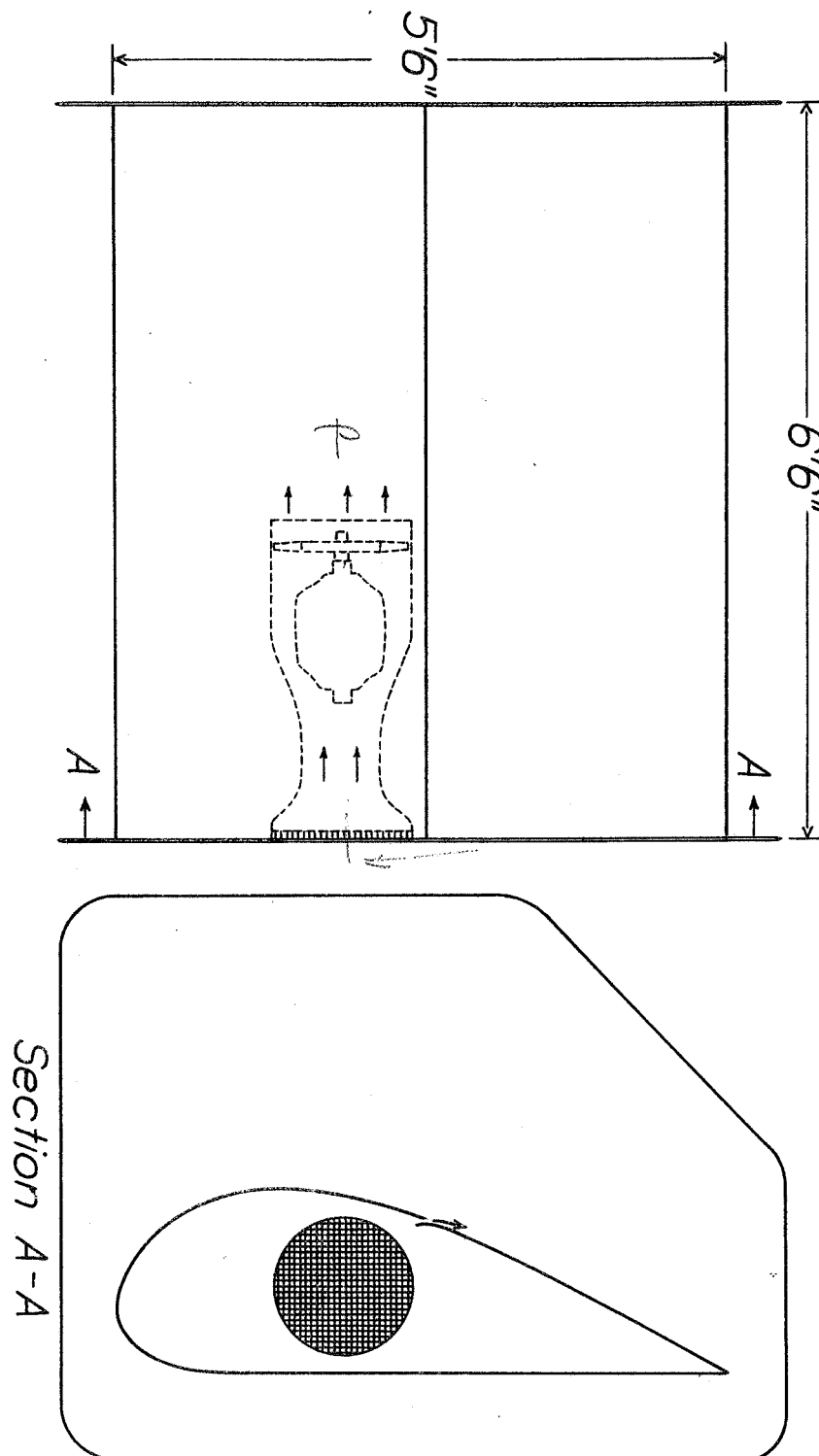


Figure 1.- Wing and blower for boundary-layer tests.
Pressure-slot arrangement.

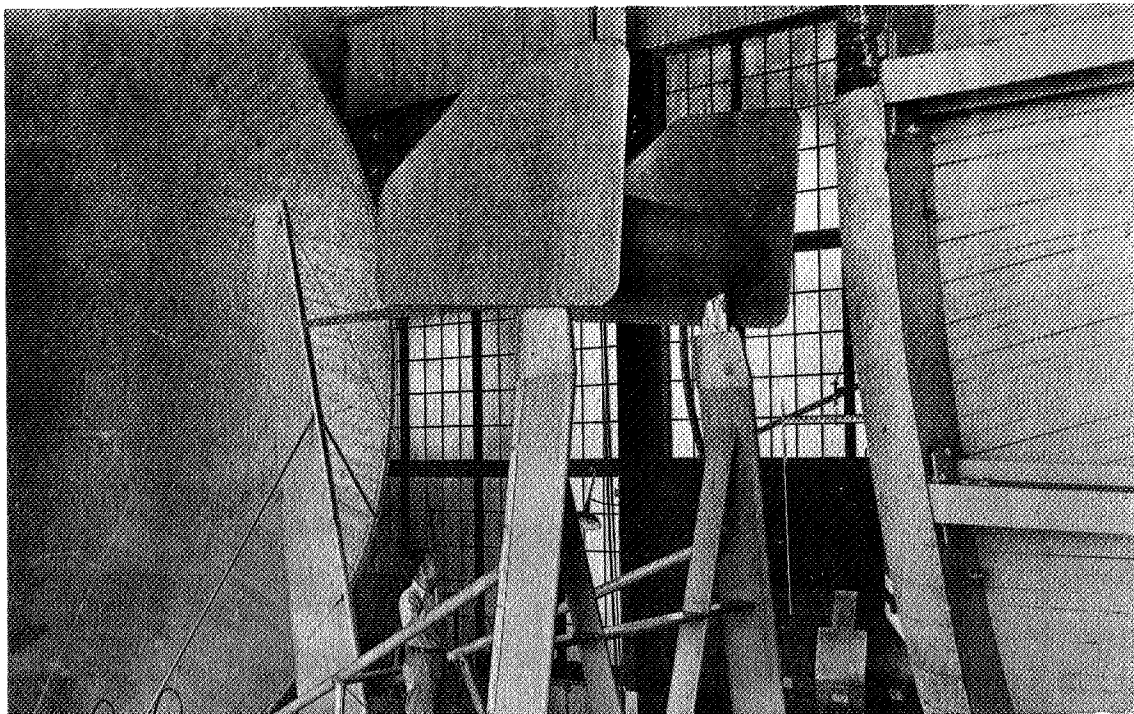


Figure 2.

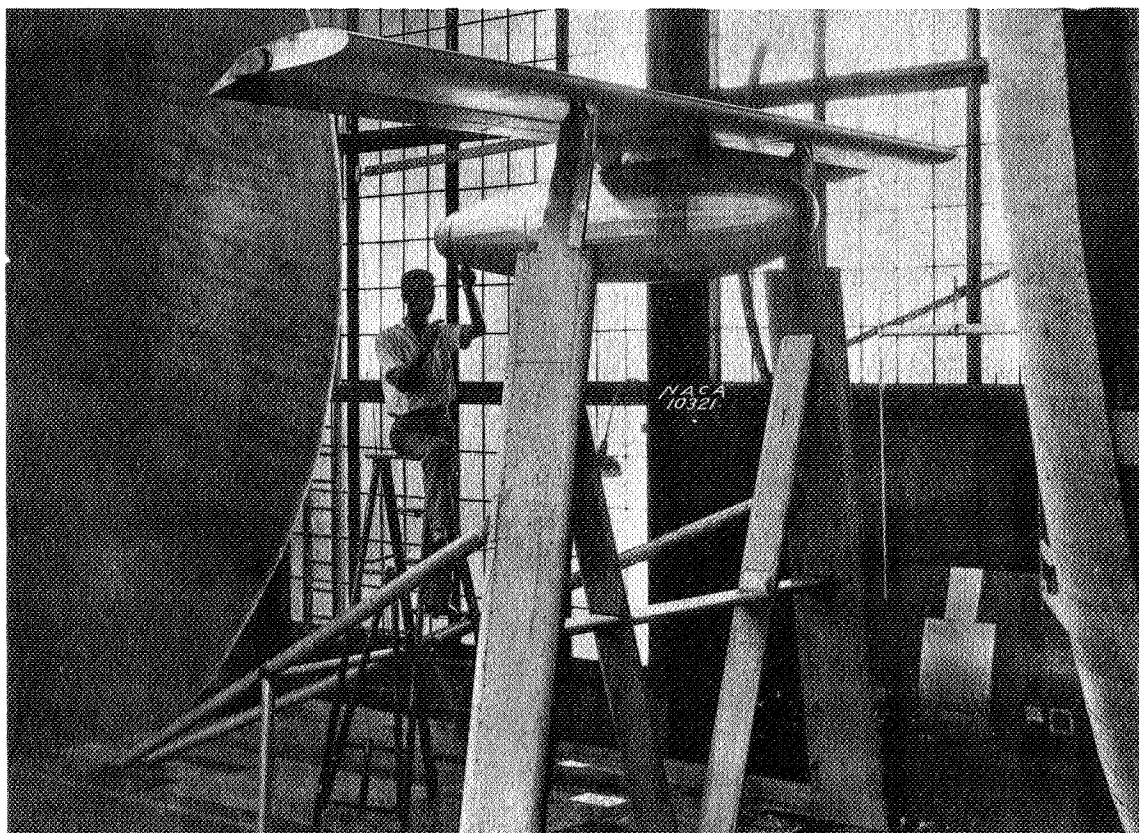


Figure 3.

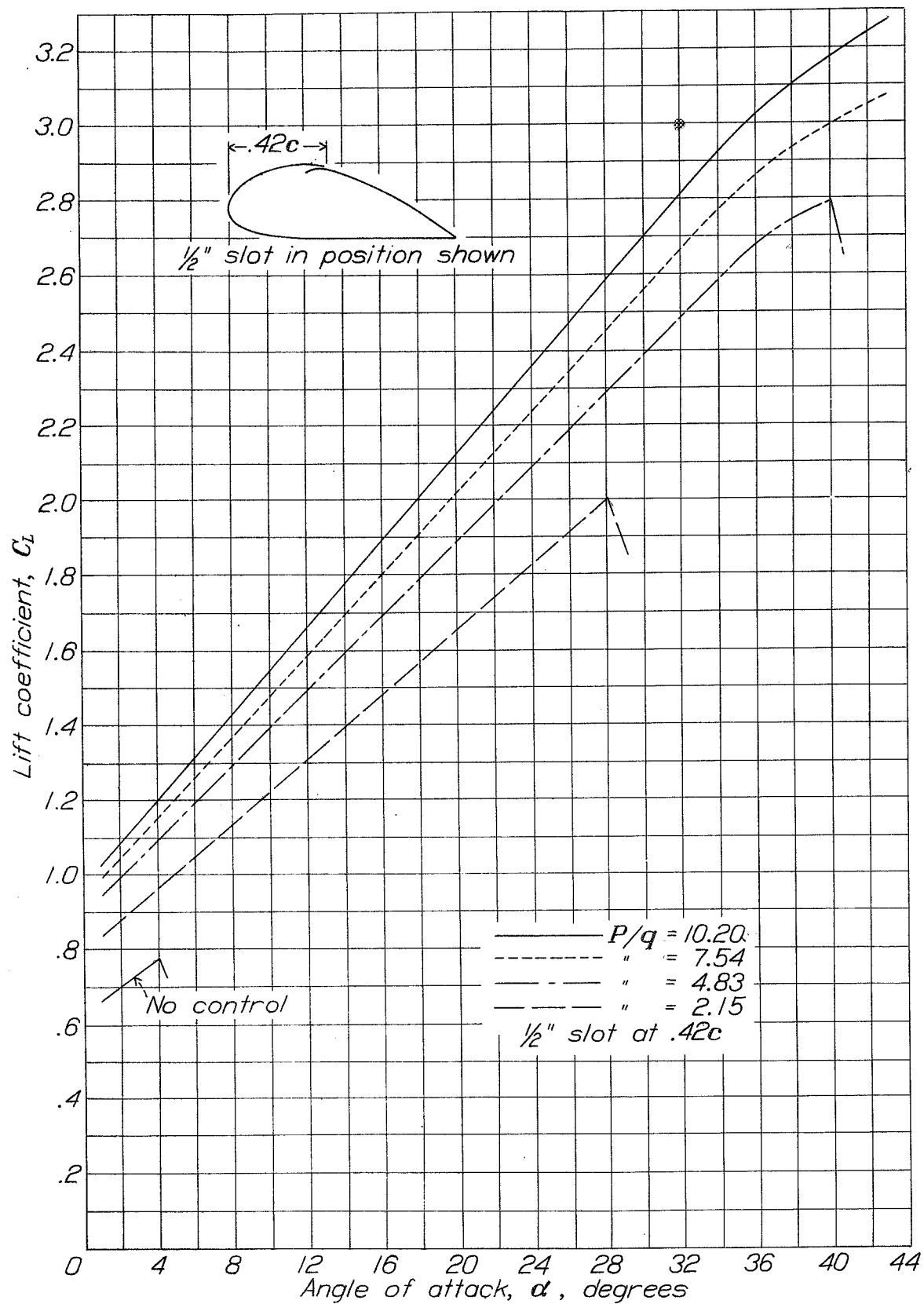


Figure 4.- Effect of wing pressure on lift. Backward-opening pressure slot

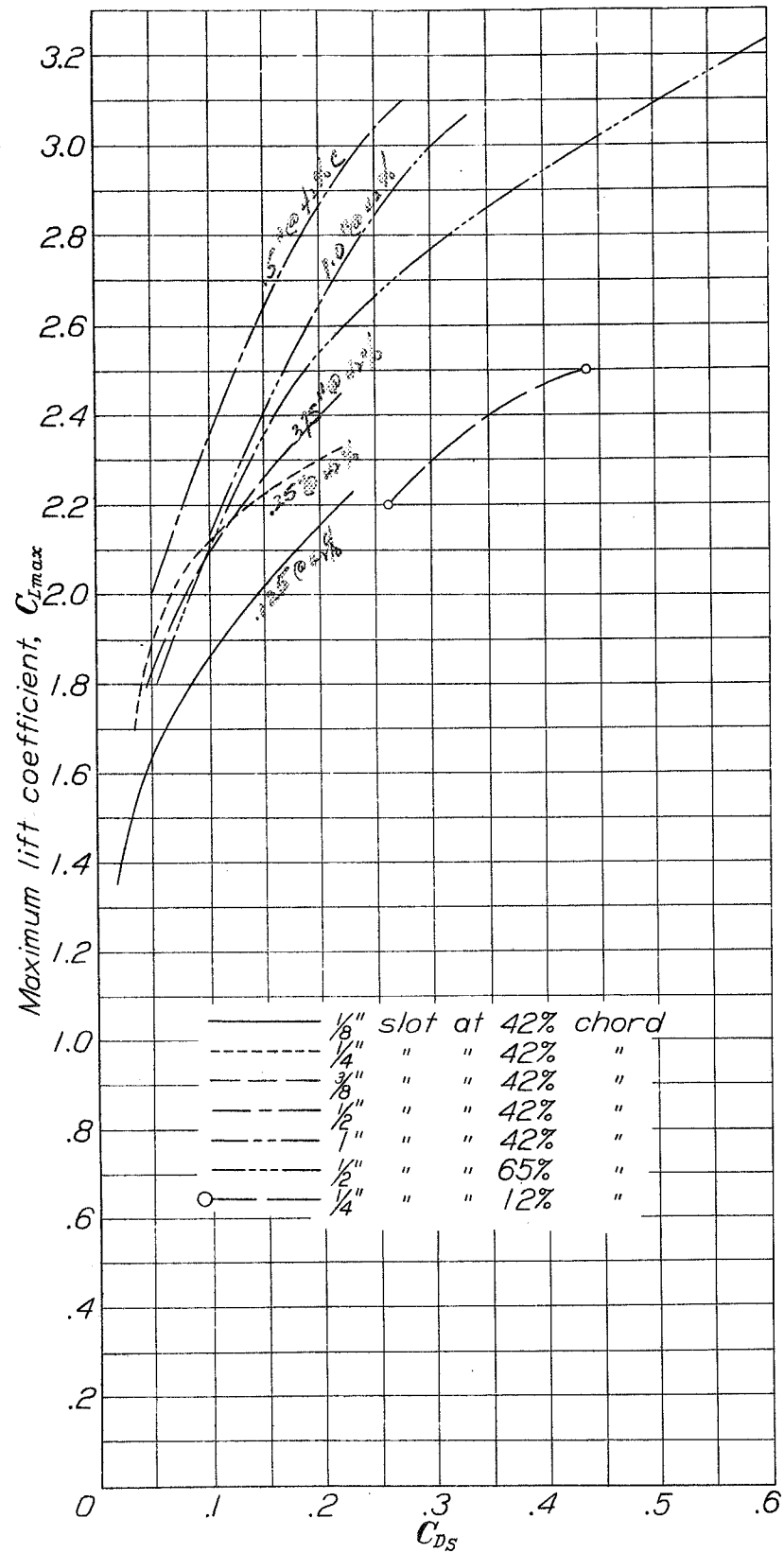


Figure 5.- Backward opening pressure slots.

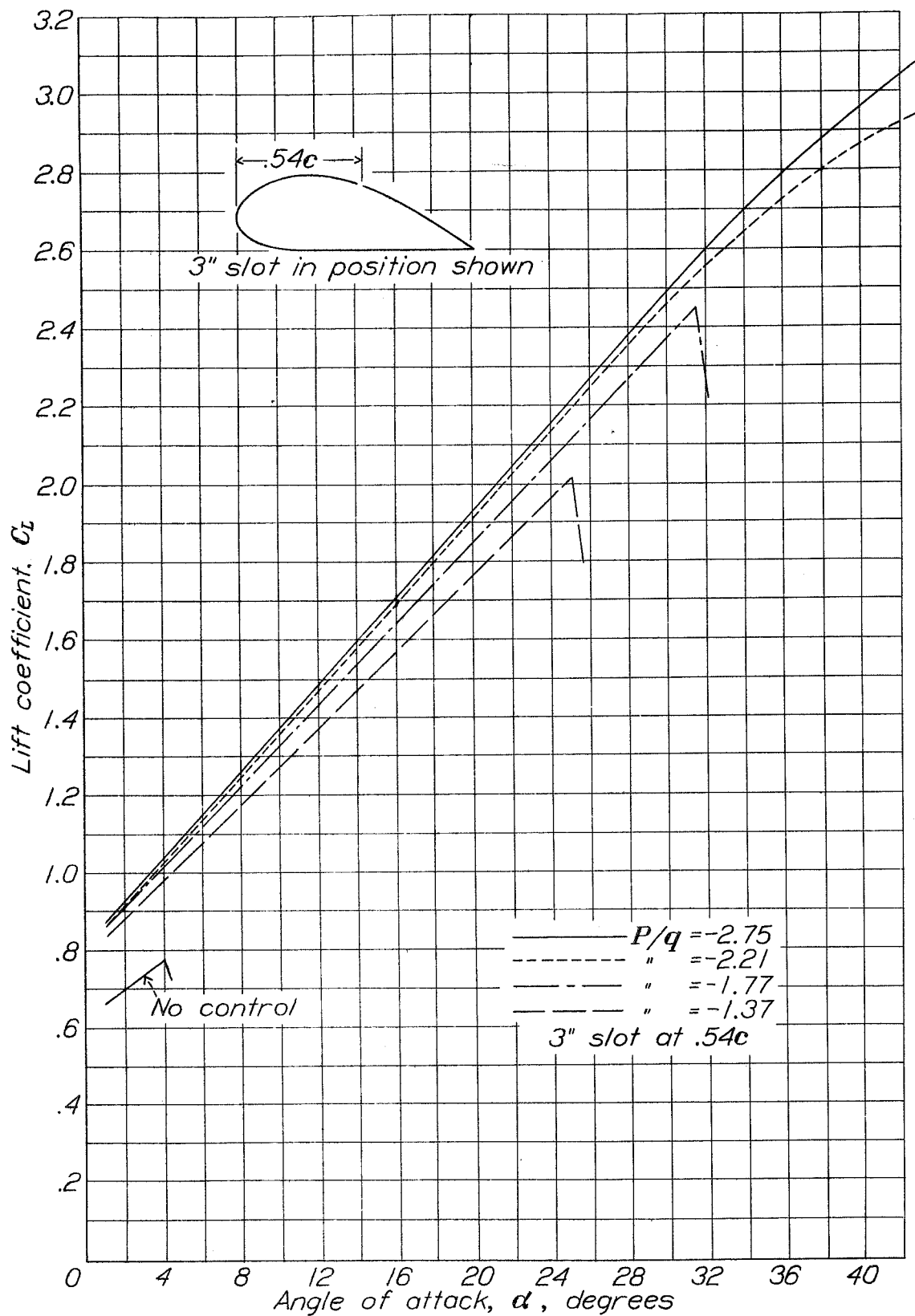


Figure 6.- Effect of wing pressure on lift. Suction slot normal to surface.

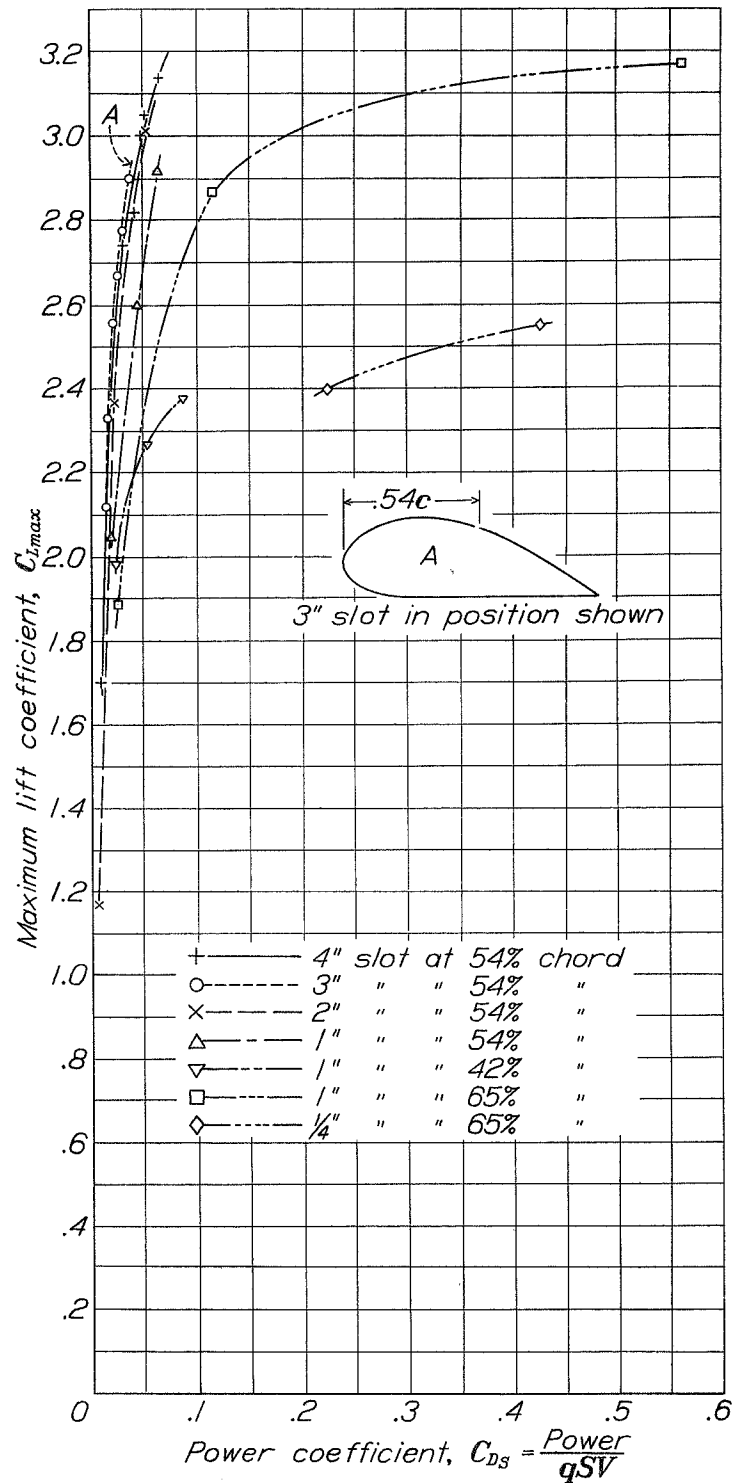


Figure 7.- Large suction slots normal to surface.

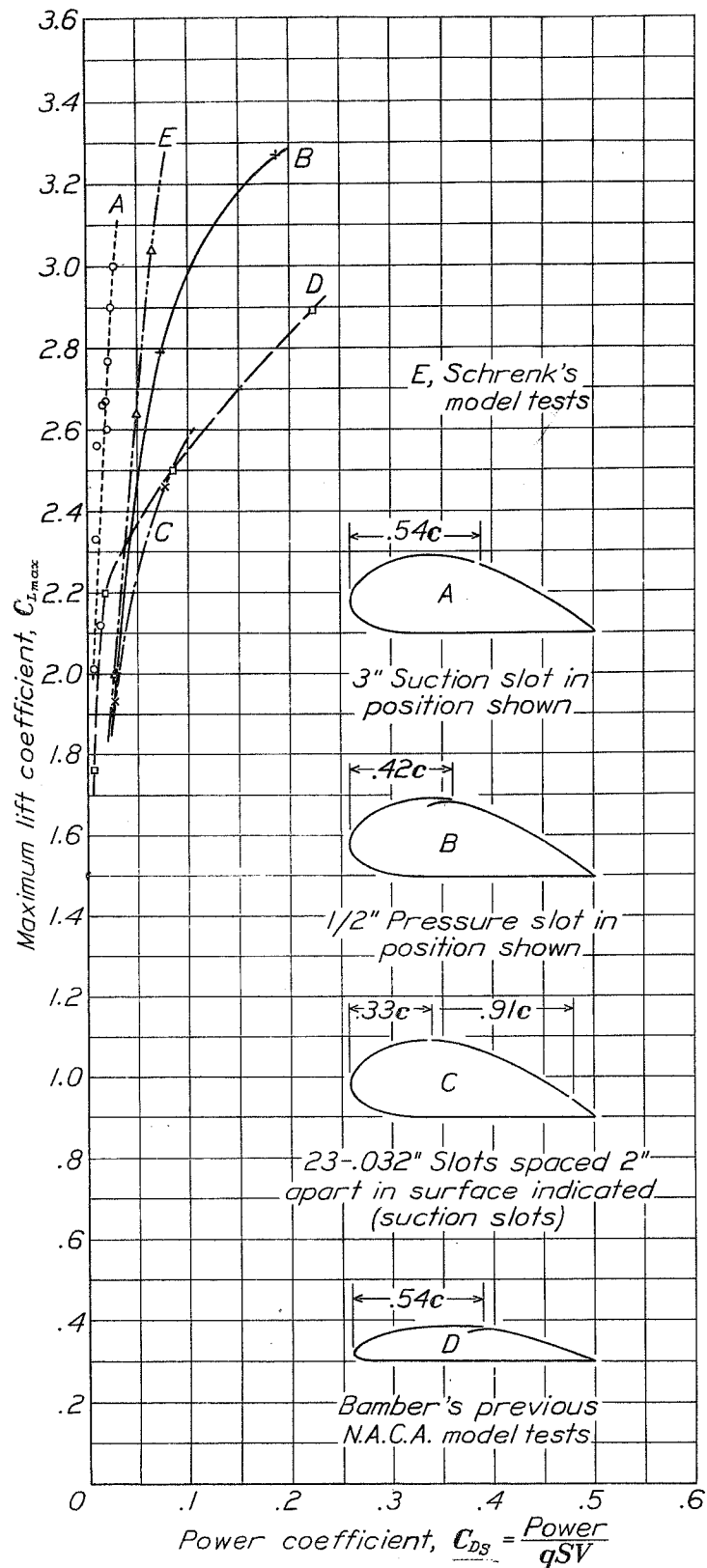


Figure 8.- Comparison of most favorable slot arrangements with previous model tests. Ideal blower.

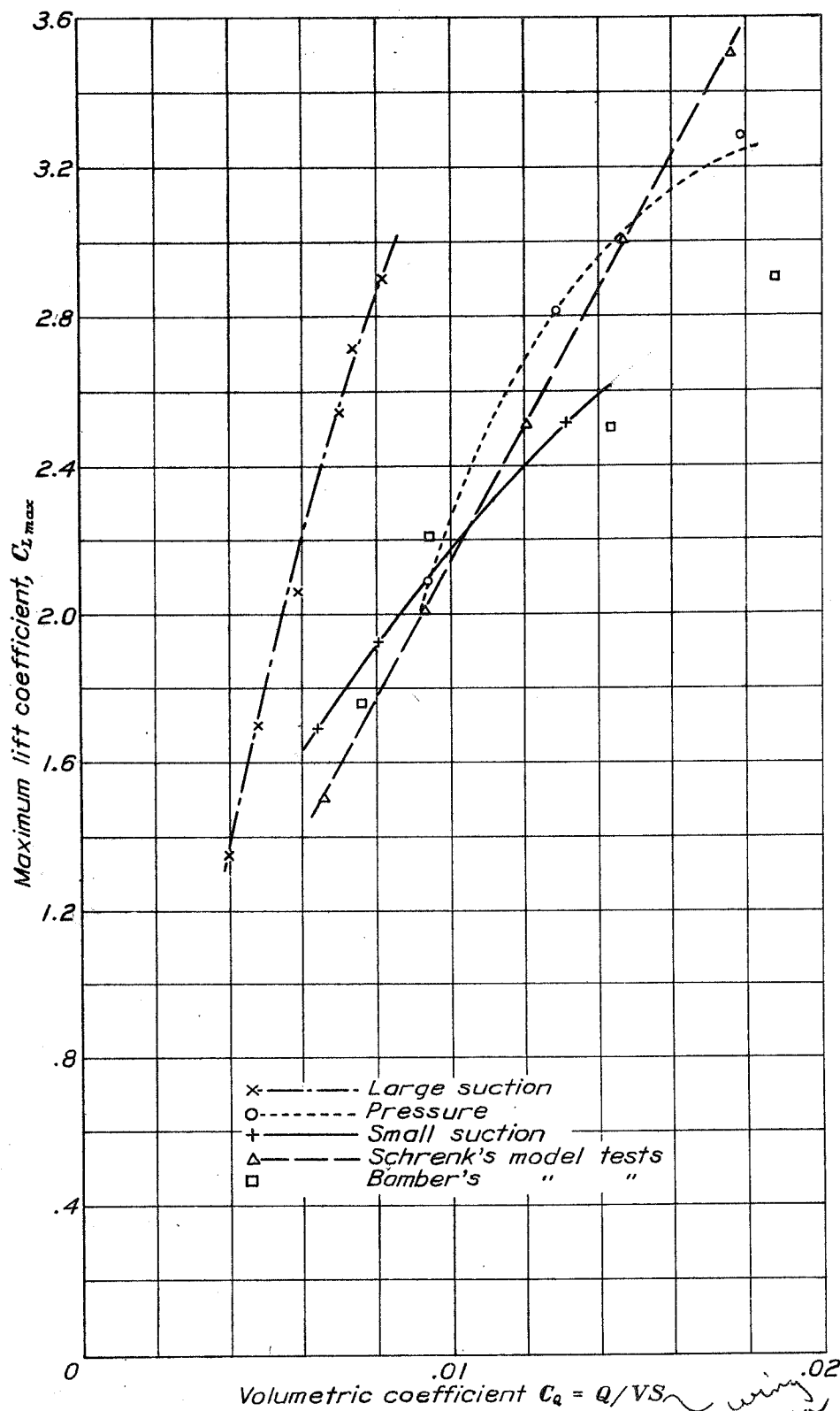


Figure 9.— Comparison of most favorable slot arrangements with previous model tests.

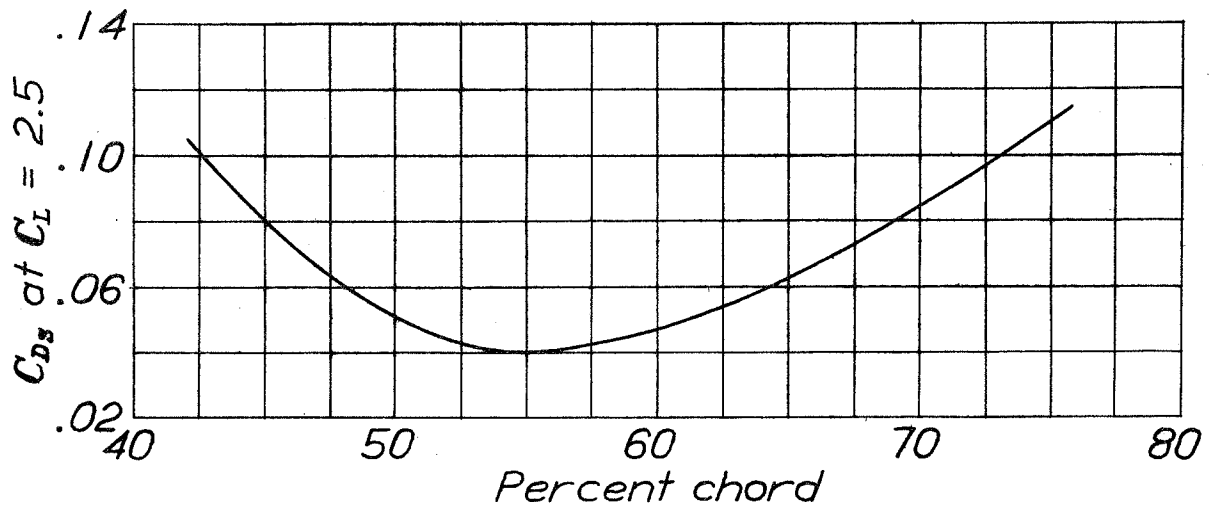


Figure 10.- Effect of slot position on power coefficient. One inch suction slot.

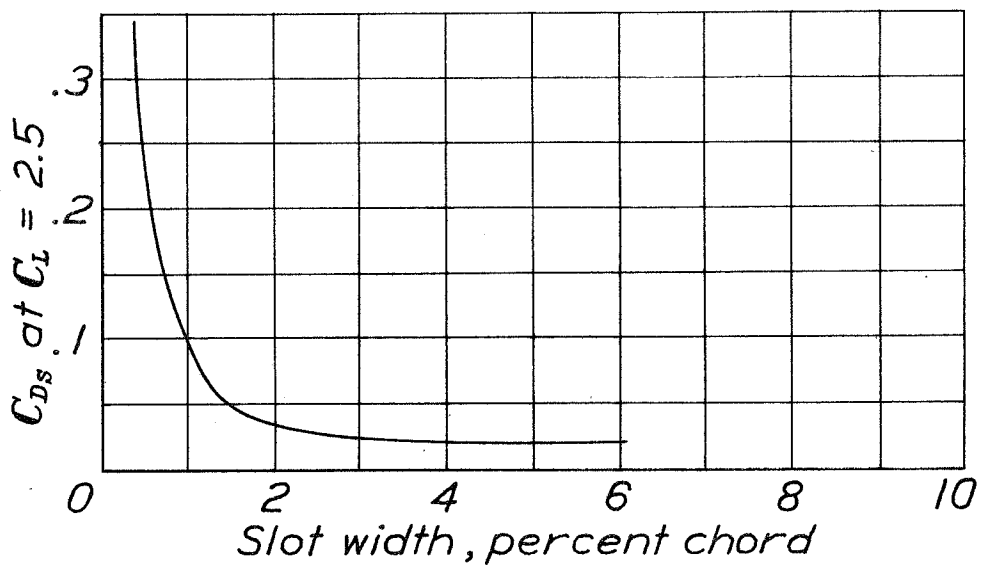


Figure 11.- Effect of slot width on power coefficient. Suction slots

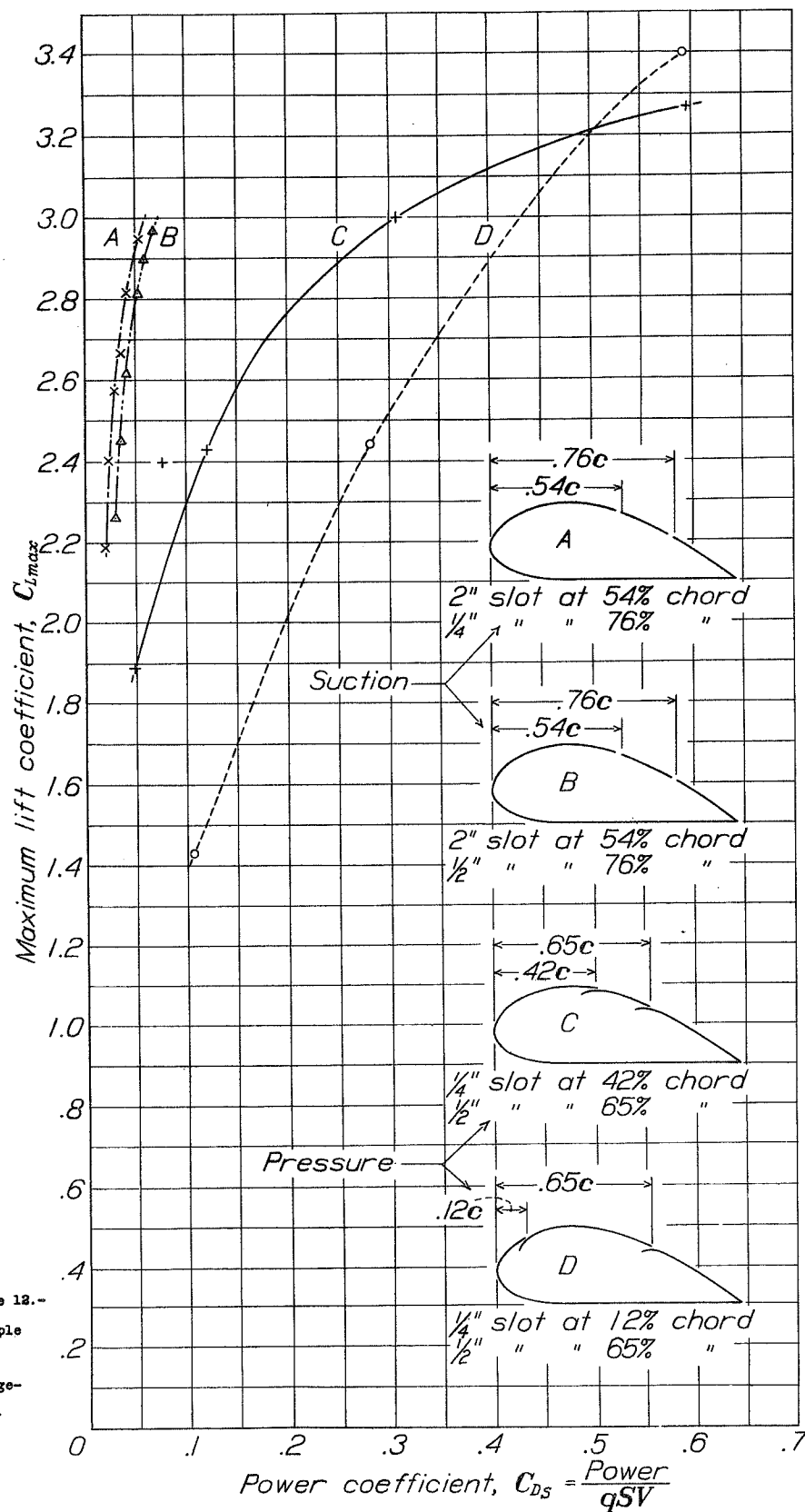


Figure 12.-
Multiple
slot
arrange-
ments.

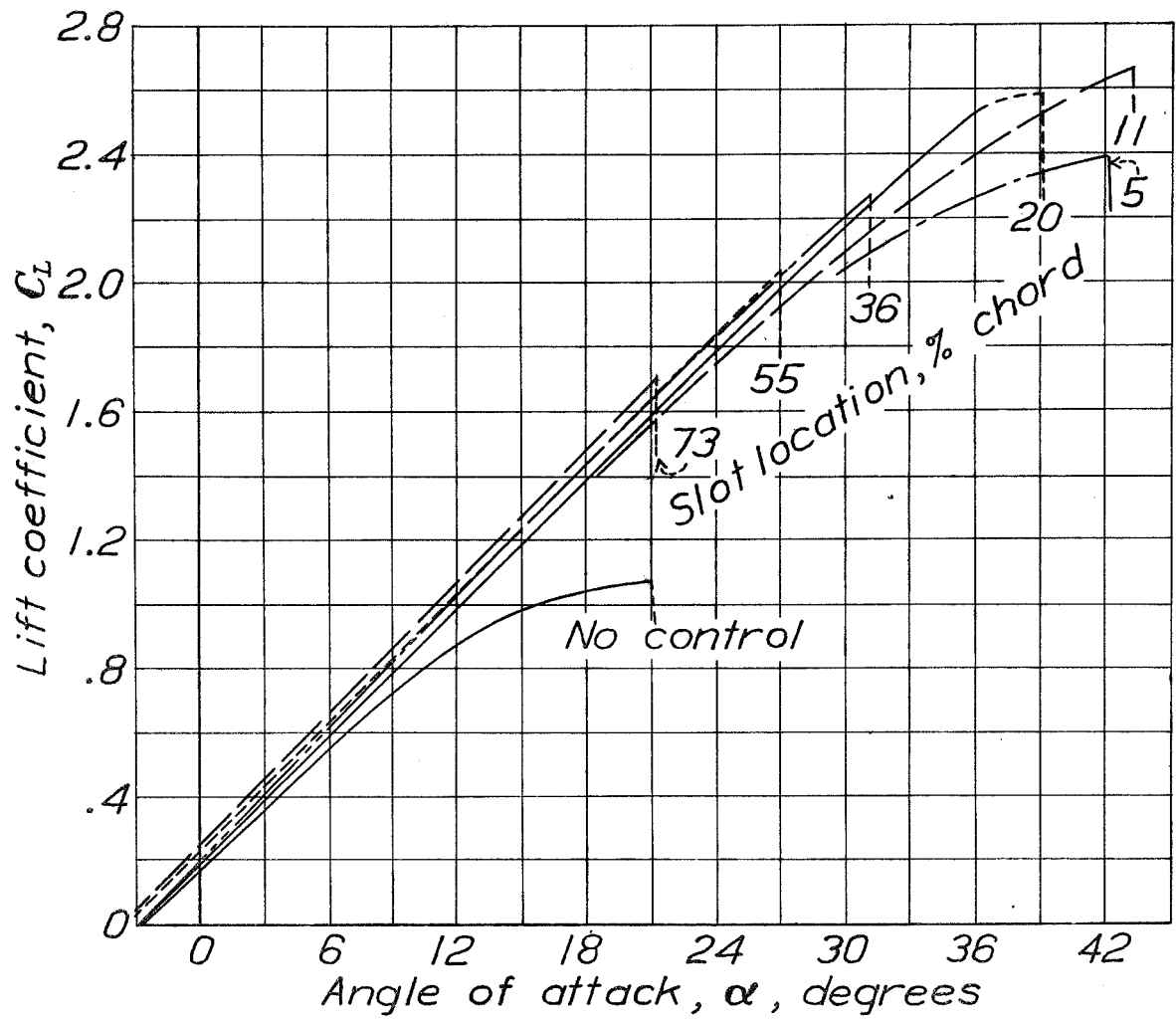


Figure 13.- Effect of slot location on lift of plain wing.
Blower speed constant.

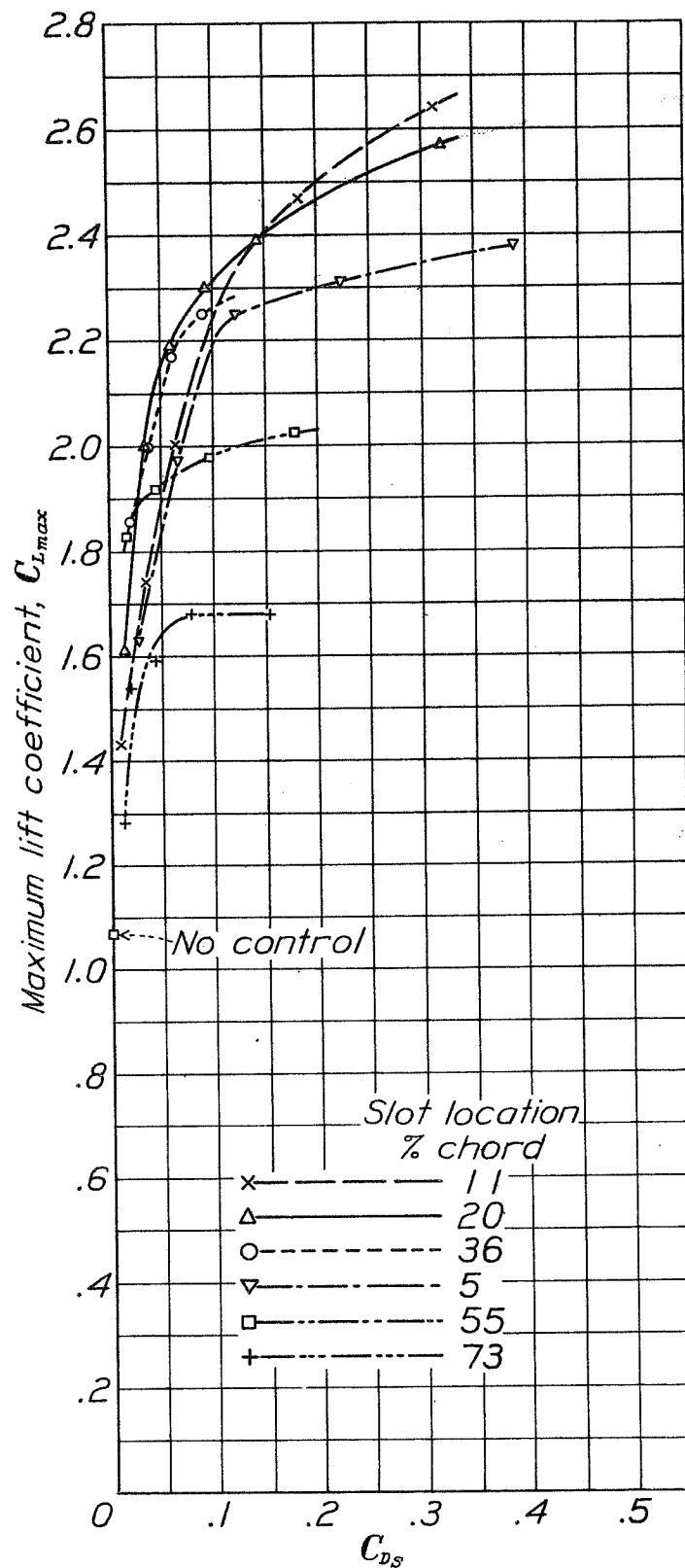


Figure 14.- Variation of maximum lift with blower power and slot location. Normal wing. Ideal blower.

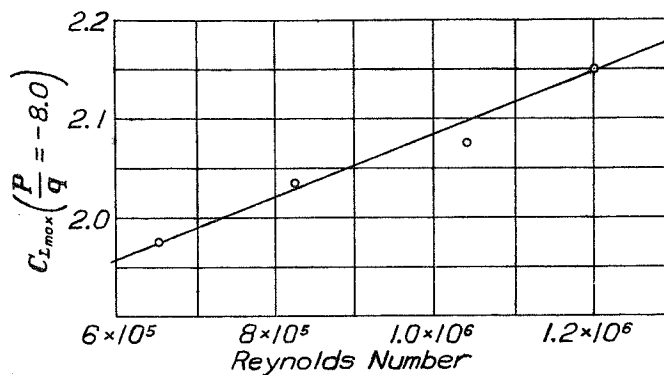


Figure 15. -
Effect of
scale on
maximum
lift.
Normal
wing

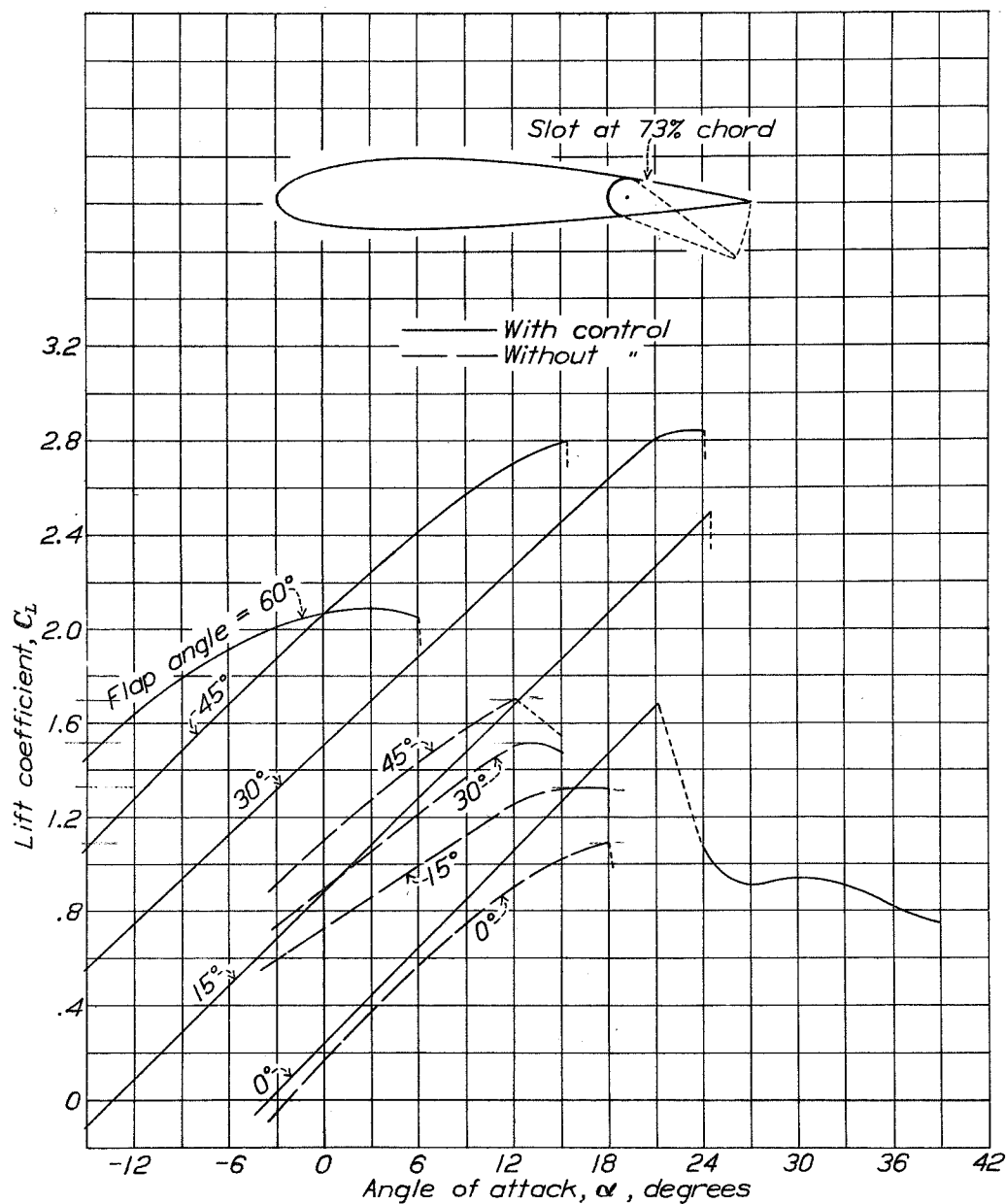


Figure 16.- Comparison of lift with and without control, slot on flap. Wing with plain flap. Blower speed constant.

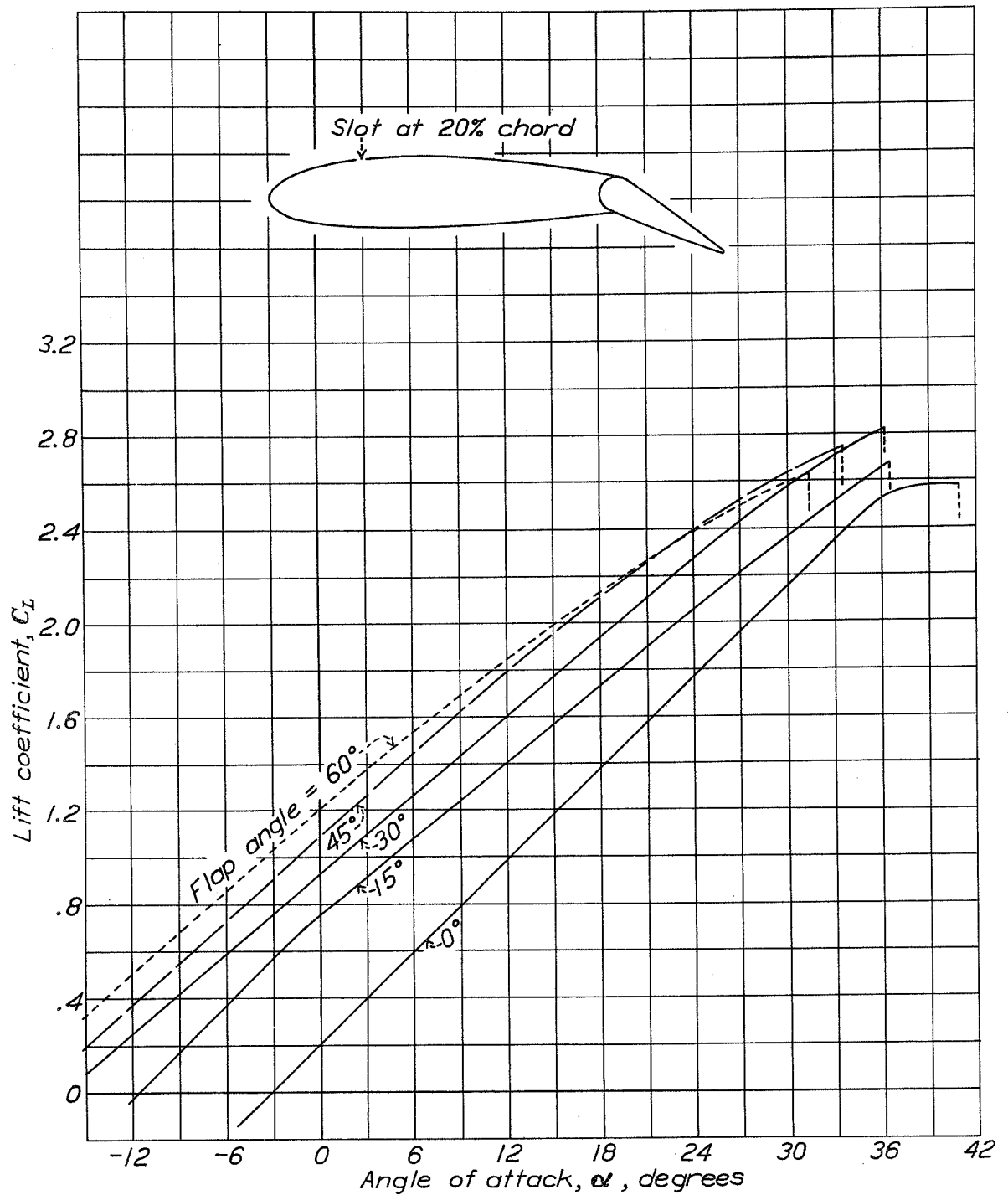


Figure 17.- Lift curves with slot on main wing. Wing with plain flap. Blower speed constant.

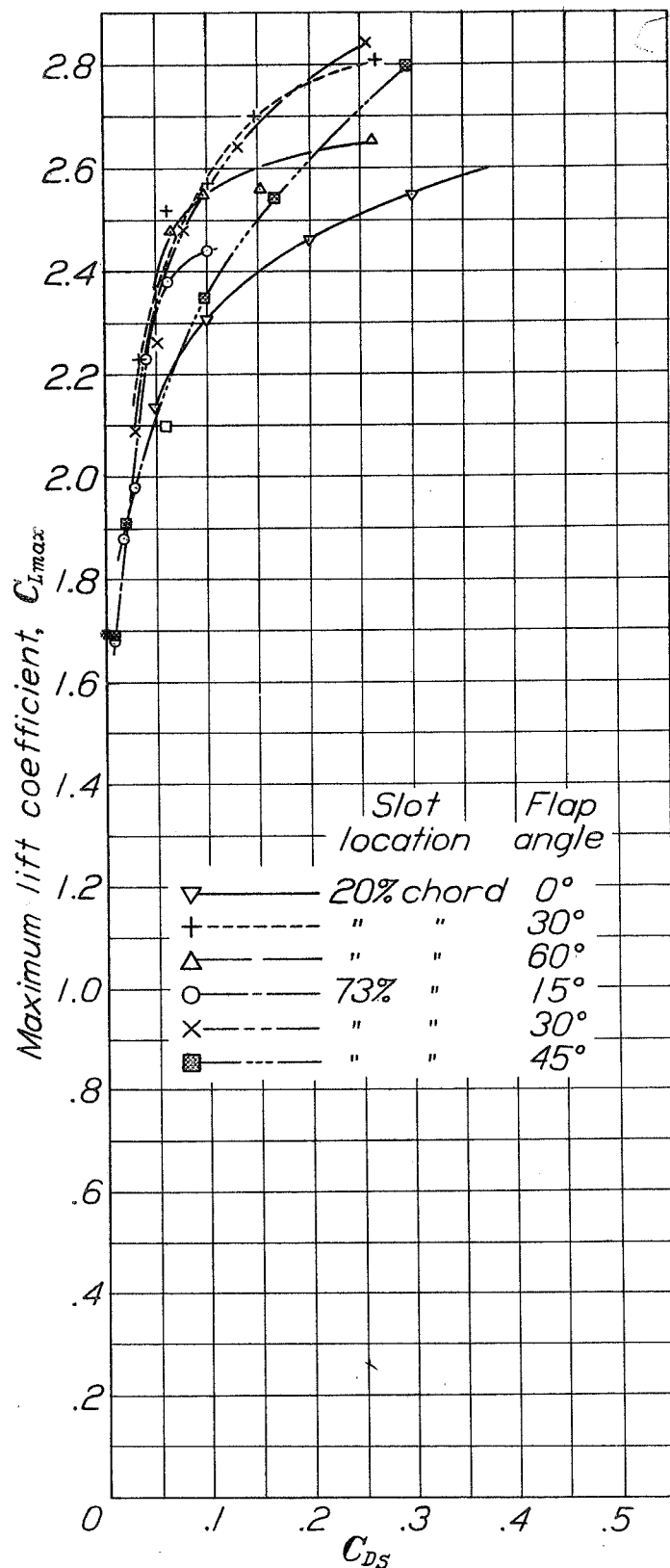


Figure 18.- Maximum lift variation with blower power.
Plain flap. Ideal blower.

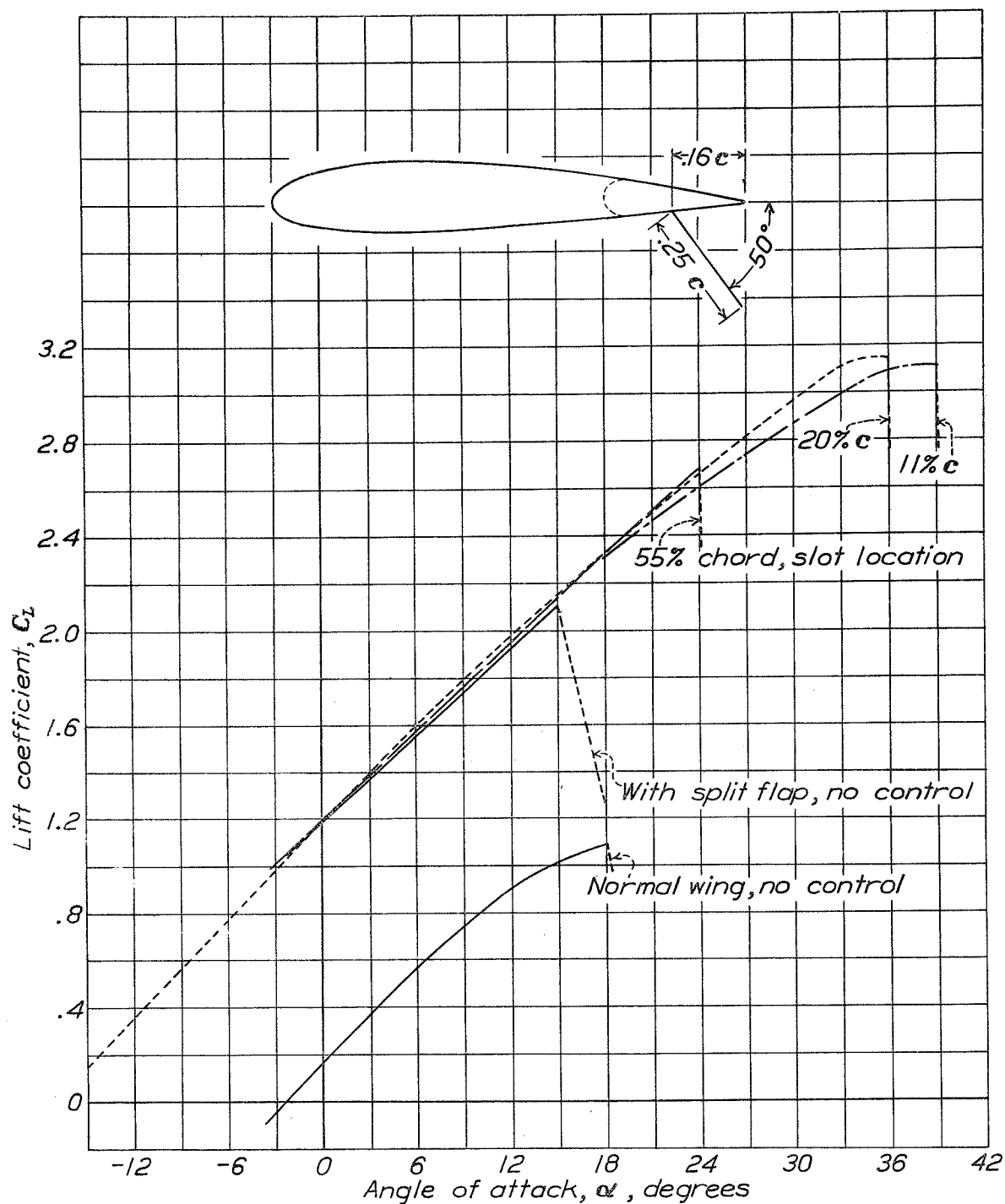


Figure 19.- Lift curves with and without control. Wing with split flap. Blower speed constant.

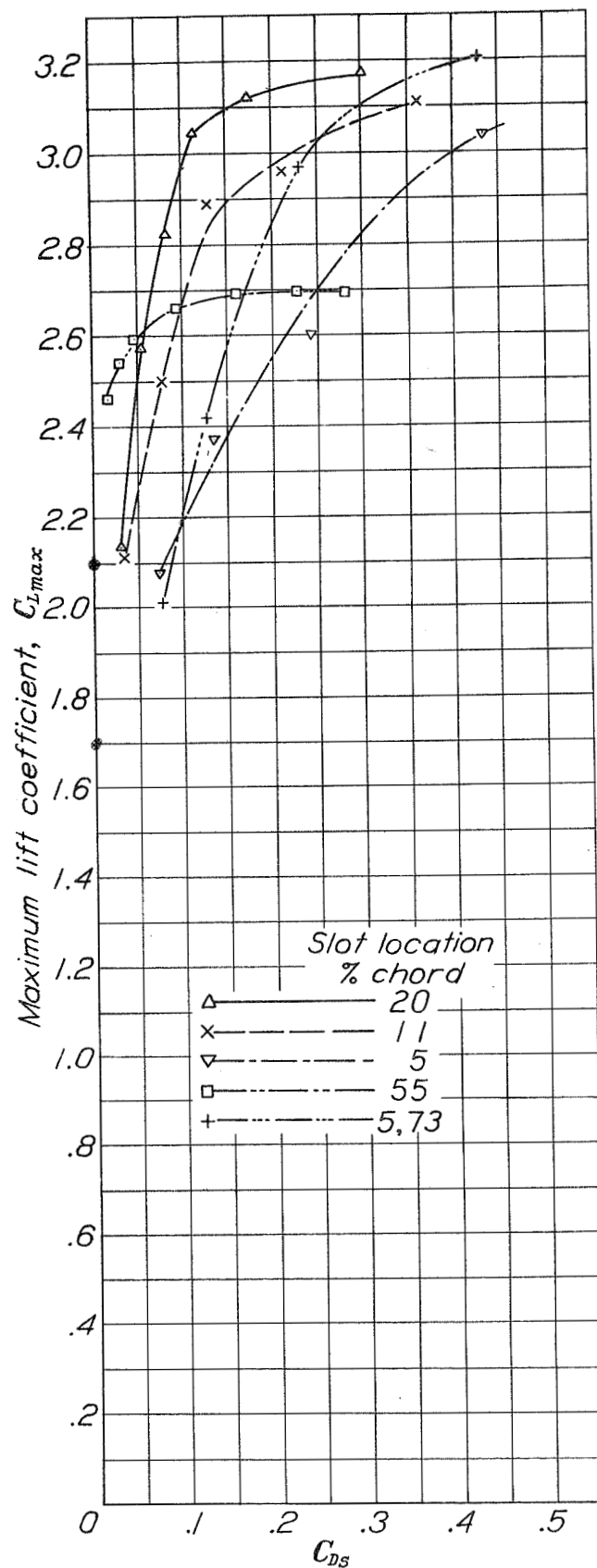


Figure 20.- Maximum lift variation with blower power.
Split flap 50°. Ideal blower.

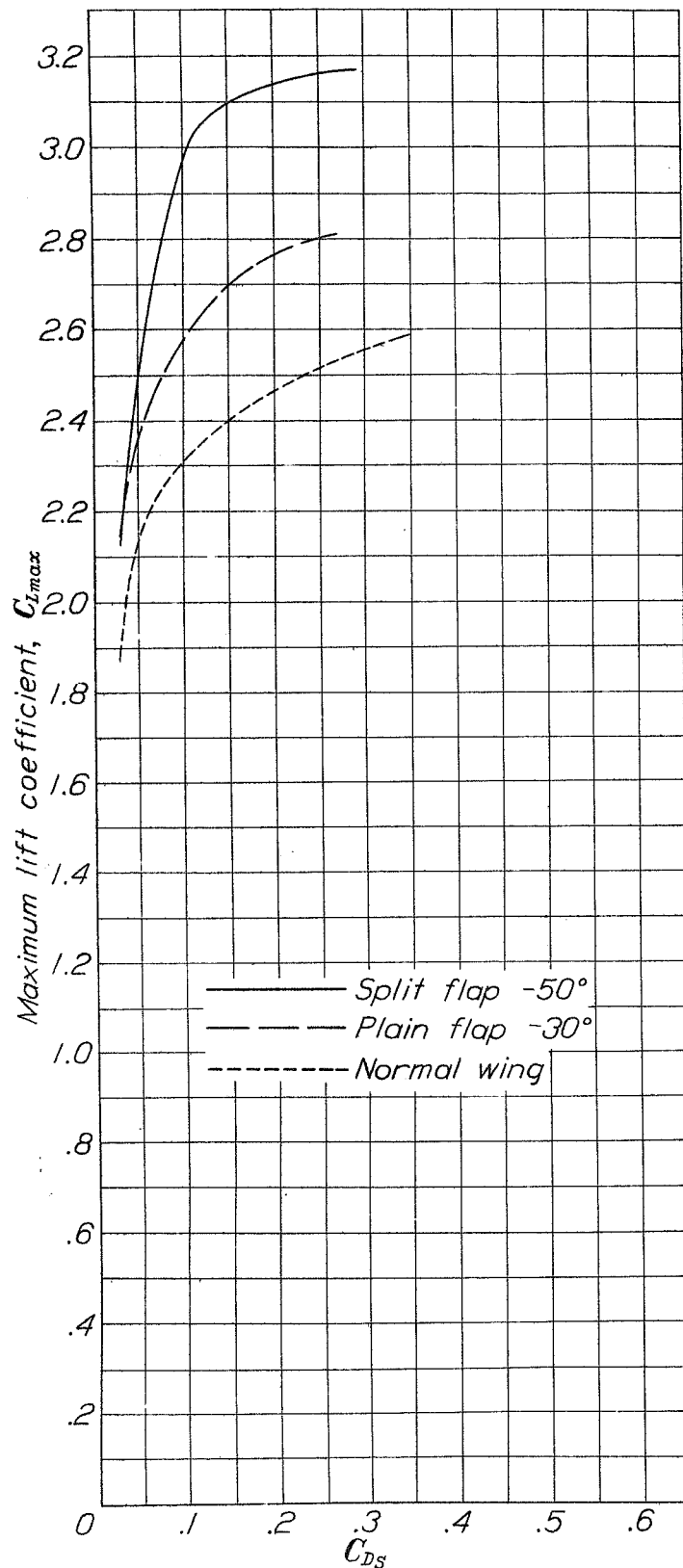


Figure 21.- Comparison of maximum lift with normal wing, plain flap and split flap. Ideal blower.

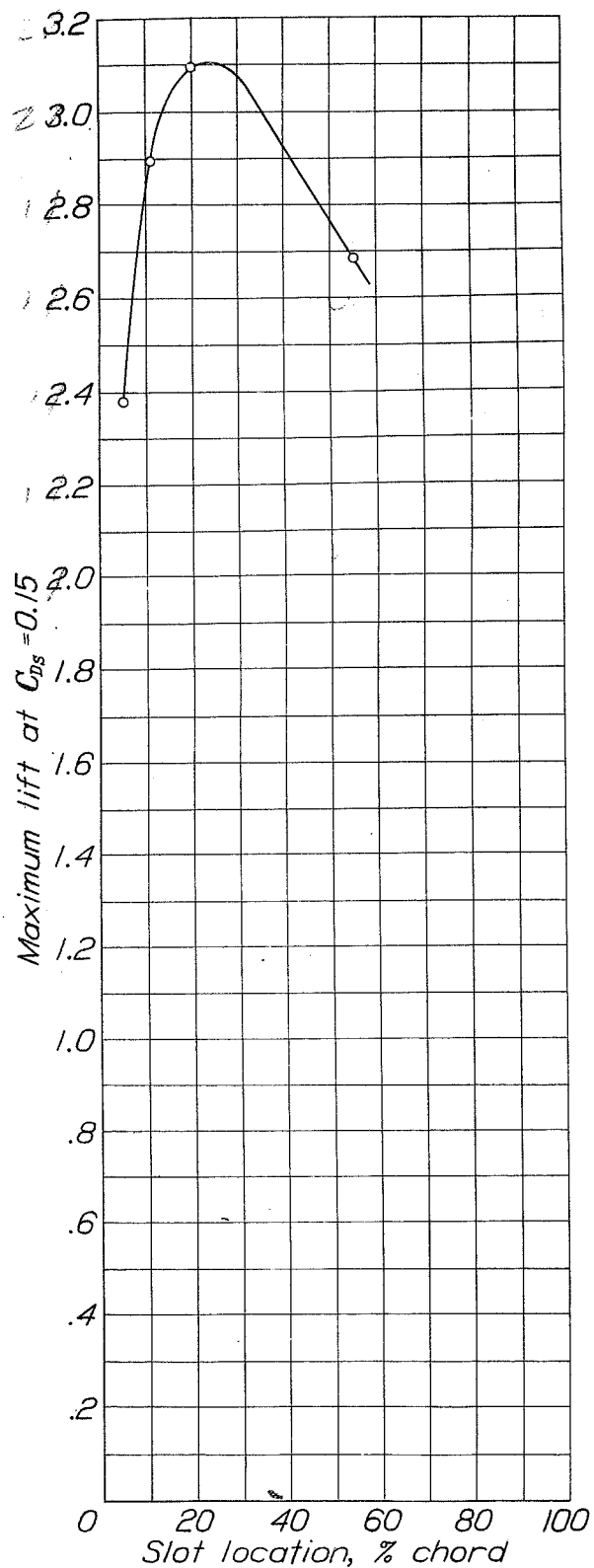


Figure 22.- Effect of slot location. Wing with split flap.

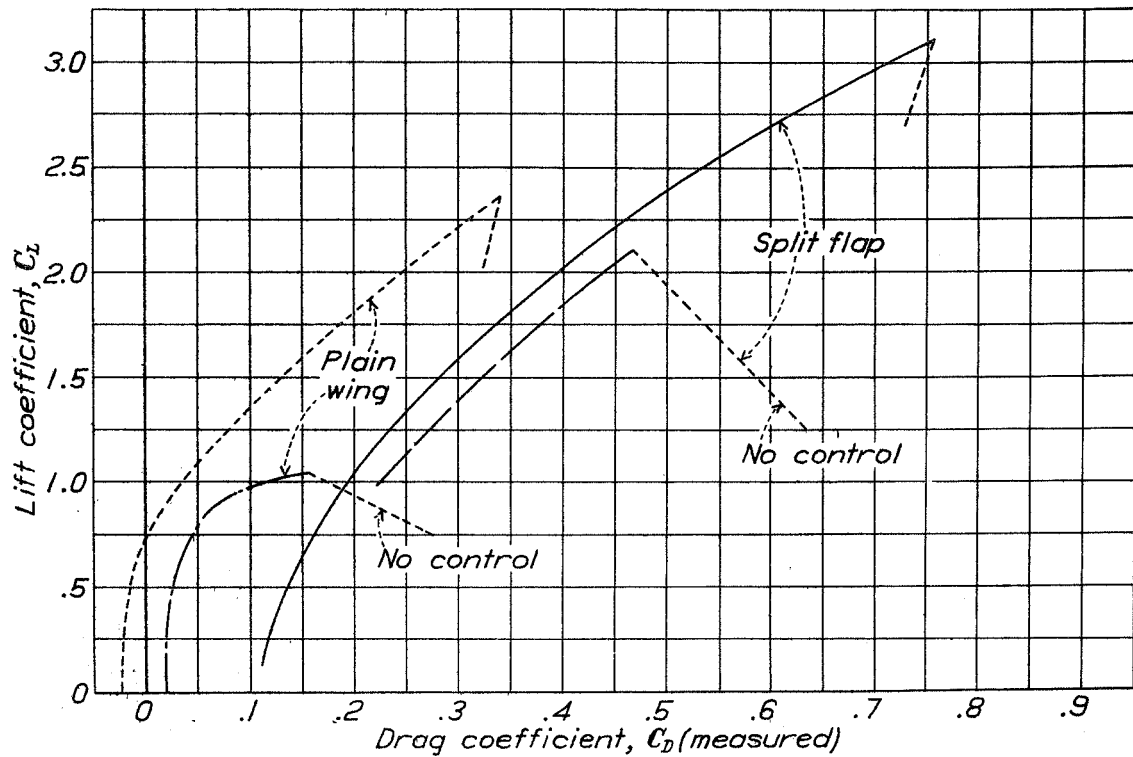


Figure 23.- Wing characteristics with and without control for gliding flight.

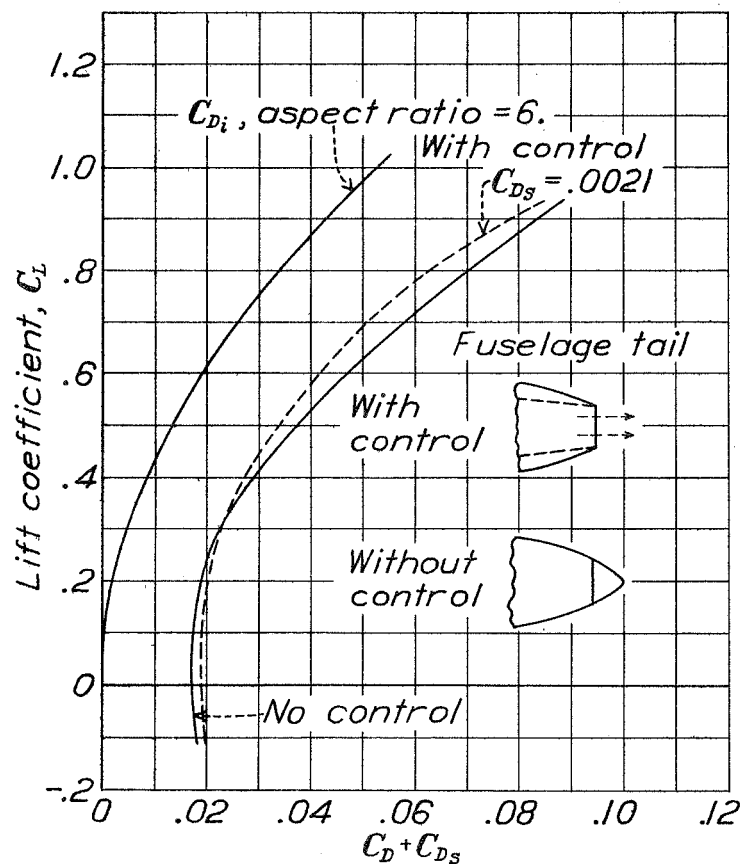


Figure 24.-
Slot
at
91 percent
chord,
plain
wing